Relationships between the Bulk-Skin Sea Surface Temperature Difference, Wind, and Net Air-Sea Heat Flux
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INTRODUCTION

The primary purpose of this project was to evaluate and improve models for the bulk-skin temperature difference to the point where they could accurately and reliably apply under a wide variety of environmental conditions. To accomplish this goal, work was conducted in three primary areas. These included production of an archive of available data sets containing measurements of the skin and bulk temperatures and associated environmental conditions, evaluation of existing skin layer models using the compiled data archive, and additional theoretical work on the development of an improved model using the data collected under diverse environmental conditions. In this work we set the basis for a new physical model of renewal type, and propose a parameterization for the temperature difference across the cool skin of the ocean in which the effects of thermal buoyancy, wind stress, and microscale breaking are all integrated by means of the appropriate renewal time scales. Ideally, we seek to obtain a model that will accurately apply under a wide variety of environmental conditions. A summary of the work in each of these areas is included in this report.

A large amount of work was accomplished under the support of this grant. The grant supported the graduate studies of Sandra Castro and the preparation of her thesis which will be completed later this year. This work led to poster presentations at the 1999 American Geophysical Union Fall Meeting [2] and 2000 IGARSS meeting [3]. Additional work will be presented in a talk at this year's American Meteorological Society Air-Sea Interaction Meeting this May [4]. The grant also supported Sandra Castro during a two week experiment aboard the R/P Flip (led by Dr. Andrew Jessup of the Applied Physics Laboratory) to help obtain additional shared data sets and to provide Sandra with a fundamental understanding of the physical processes needed in the models. In a related area, the funding also partially supported Dr. William Emery and Daniel Baldwin in the preparation of their publication "Accuracy of in situ sea surface temperatures used to calibrate infrared satellite measurements" [9]. The remainder of this report is drawn from these publications and presentations.

THEORETICAL BACKGROUND

In order to understand the relationship between the water temperature measured at some depth by a ship or a buoy (bulk temperature) and that obtained from an infrared radiometer (skin temperature), it is necessary to understand the processes taking place at the sea-water interface. In the top 10 to 100 microns of the ocean surface, the transport of fluxes is dominated by molecular conduction. In order to maintain a net heat flux from the ocean to the atmosphere there needs to be a positive temperature gradient with depth across the molecular layer. As a result of this vertical heat exchange, a cool skin adjacent to the ocean surface prevails under most circumstances. An extensive amount of work has gone into attempting to model and predict the temperature difference across the skin layer, $\Delta T = T_{skin} - T_{bulk}$. Traditional models, in analogy with atmospheric processes, consider two essential mechanisms governing the turbulent transport of heat across the molecular skin layer: *free convection* generated by the thermal instability and the salinity gradient proper of the cool skin itself and *forced convection* arising from the shear flow driven by the surface shear stress. The earliest models concentrated in one or the other driven mechanism. The first of such models was proposed by [20], who assumed the dominance of forced convection in the skin layer except under calm wind conditions when

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buoyancy-driven convection is the responsible mechanism for the transfer of heat [14]. Subsequent efforts dealt with incorporating a transition between these two mechanisms in a parameterization for ΔT through a proportionality constant dependent on wind speed [10]. In any case, the focus of these models has been in estimating the thickness of the molecular skin layer using approximations based on shear flows in rigid-wall layers. Once the thickness of the skin layer is known, an estimate for ΔT directly follows from the net heat flux equation. Comprehensive reviews of these early efforts can be found in [14], and [19].

Another group of parameterizations was developed from a different background based on the theory of surface renewal [1], [15], [21], [23], and [25]. The surface renewal theory assumes that at regular or irregular intervals a part of the surface layer is removed and replaced by water from the bulk. The mean time between successive surface renewal events, called *the surface renewal timescale*, is the primary focus of this type of models. Classic renewal events include overturning instabilities caused by either free convection or forced convection due exclusively to surface shear stress. The surface renewal parameterizations, however, apply only on the scale of the renewal eddies which is taken to be the Kolmogorov length scale (smallest possible eddies). From this assumption it follows that the only difference between the models rooted on "the law of the wall approximation" and the models based on surface renewal theory is whether or not the fluid from the molecular sublayer remains intact [24]. A more recent review on this trend of ΔT parameterizations is presented by [25].

At high wind speeds, breakdown of the thermal skin layer occurs due to the onset of white-capping. Although large-scale wave breaking is known to be rather scarce in the open oceans [28], there is general consensus on the ubiquity of small-scale breaking without air entrainment or *microscale breaking*. Even after an early recognition that sea surface temperatures vary with the phase of surface waves, the effect of waves on the ocean skin temperature has been excluded from the traditional parameterizations of ΔT. Most models have been developed under the assumption of no wave stirring conditions or smooth wall boundary approximations. That is not to say that this aspect has not received its proper share of attention. Theoretical [27], experimental, both in the laboratory ([5], [17]) and in the field ([22], [13]), and more recently, numerical ([26], [8]) studies have advanced our understanding of the air-sea interaction and surface waves separately. Nevertheless, studies of the combined effects of the three forcing mechanisms under consideration, namely, wind input, wave interaction, and buoyancy, are still scarce both theoretically and experimentally. Further progress of theoretical modeling is hindered partly because to extent to which laboratory results may be scaled to natural conditions remain open [7], [12], and partly because reliable direct observations of microscale waves in a field environment are almost nonexistent except for the radar backscatter measurements that come with their own uncertainties owing to the lack of knowledge regarding the mechanism of microwave reflection at the air-sea interface [6].

As a result of the challenges presented by laboratory and field observations of wave related processes, theoretical modeling of ΔT has been limited to the simple approach based on the net heat flux with the above three mechanisms added independently and exclusively on the basis of some specified threshold determined by either the wind speed or the friction velocity as given by the surface Richardson number [23]. Figs. 1 and 2 show how well the diverse datasets from ten different field experiments conform to the existing parameterizations summarized in [14] and [25]. Despite this work, the aforementioned studies are still unable to accurately predict ΔT under the full range of environmental conditions encountered. Models derived in one region or during one period provided reasonable correlations within individual datasets but when the diverse datasets are combined covering a broad range of conditions, these correlations are significantly degraded. Discrepancies remain between the different models that cannot be resolved by the currently available parameterizations, specially for extreme weather conditions when field observations are most challenging. Moreover, they still fail to fully account for microscale breaking.

IN-SITU DATA

The first element of this work was to compile an archive of as many data sets containing coincident in situ measurements of the skin and bulk temperatures and environmental forcing conditions as possible. Researchers throughout the community were contacted and asked to contribute to this data archive. As a result, a large data set containing a sample of measurements from extremely diverse instrumentation and environmental regimes was collected. This section summarizes the primary data sets that compose this archive.

An infrared radiometer is ideally suited for measuring the skin temperature since the optical depth of $O(10^{-5}\,m)$ is much less than the skin layer thickness of $O(10^{-3}\,m)$. On the other hand, the bulk temperature is recorded by ship measurement techniques (resistance thermometers) a few meters below the surface. The spacing between measurements imposes a problem in determining accurate ΔT at least during the day. A diurnal thermocline may develop which imposes a strong thermal gradient within the first meters of the surface overlapping with the skin effect. For this reason only nighttime measurements will be considered in this study. Additionally, since a small temperature difference is sought between the temperatures measured by two different instruments and techniques, the demands on the absolute accuracy of both instruments is very high. The following experiments have generated state-of-the-art data sets, collected in many different regions during the course of several cruises, accurate enough for a detailed investigation of ΔT and the transport of heat and momentum at the air-sea interface.

The initial analysis were performed on a data set taken during the Radiometric Observations of the Sea Surface and Atmosphere (ROSSA) 1996 experiment aboard the British Research Vessel RRS *James Clark Ross* (JCR) while on passage from the UK to the Falkland Islands, between September 19th and October 21st of 1996. This data set was collected by Dr. Craig Donlon of the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado in collaboration with the Rutherford Appleton Laboratory (RAL), the Southampton Oceanography Center (SOC) and the Atlantic Meridional Transect experiment 3 (AMT-3). The following instrumentation was deployed during the ROSSA 1996 experiment:

a.) Sea surface temperatures:

- The skin sea surface temperature (T_{skin}) was radiometrically determined using the Scanning Infrared Sea surface Temperature Radiometer -SISTeR (T. Nightingale, RAL). This is a multispectral, scanning ship-mounted infrared radiometer designed to measure the T_{skin} with an accuracy approaching $0.05\,^{\circ}K$. The SISTeR is a self-calibrated radiometer, relying on two precision blackbody cavities maintained at different temperatures. The instrument can view any point in external swath extending up from a nadir view, in addition to the two internal black bodies. For the ROSSA 1996 experiment, one blackbody was operated at the ambient temperature of the instrument and the second at $\sim 8\,^{\circ}K$ above ambient temperature. All data were collected over $0.8\,s$ sampling periods, using a single filter centered at $\sim 10.9\,\mu m$ with a bandwidth of $\sim 0.8\,\mu m$.
- The bulk sea surface temperature (T_{bulk}) was measured using the ship's thermosalinigraph. The JCR has a 'Sea-Bird' unit having an expandable intake pipe located at a depth of $5.5\,m$. Salinity samples were taken at regular intervals throughout the cruise for calibration purposes.

b.) Meteorological observations:

- The wind speed and direction were determined from a sonic anemometer system located at a height of $20\,m$ in clean air on the JCR front mast instrument table. A large range of wind speed conditions were encountered during the ROSSA 1996 experiment ranging between 0 and $22\,ms^{-1}$.
- Long- and short- wave downwelling fluxes: Eppley pyrgeometer and pyranometer instruments measuring direct downwelling long and short-wave fluxes were mounted on the dedicated upper radiometer platform of the JCR. Individual heat flux components were not directly measured but were estimated using the standard bulk formulae.
- Air temperature and humidity: An IOS WOCE standard wet- and dry-bulb psychrometer unit was used to measure air temperature and humidity from the forward mast of the JCR. This was attached to a stub pole to clear the intake area from the forward mast upper island deck which may convectively influence the PRT sensors when the deck is hot.

All available data sets were averaged over 30 second intervals.

c.) Sea surface roughness: The sea surface roughness was determined using radar backscatter measurements made at $10.525\,GHz$ (X band) using a continuous wave Doppler radar system. The sample frequency of this system is $512\,Hz$ and is an experimental system developed for use at sea by Dr. David Lyzenga from the Department of Naval Architecture and Marine Engineering at the University of Michigan, Ann Arbor. The X band transceiver was attached to a standard circular antenna of $60\,cm$ in diameter. The radar was mounted on the forward mast of the JCR to view the same area as the radiometer system and oriented to receive horizontally polarized radiation at an incident angle of 45°.

A second data set was obtained aboard the RRS *James Clark Ross* in the Atlantic Ocean in October, 1998. Like the first one, this data set was collected by Dr. Craig Donlon as part of the second phase of the Radiometric Observations of the Sea Surface and Atmosphere or ROSSA-1998 experiment. Measurements of the bulk temperature, downwelling solar and longwave radiation, and standard meteorological quantities were made in analogue to those of the ROSSA-1996 experiment. Only the skin temperature and the sea surface roughness were collected using a different set of instruments. The T_{skin} was determined using the new Ship of Opportunity Sea Surface Temperature Radiometer - SOSSTR (C. Donlon and W. Emery, CCAR). The SOSSTR system is comprised of two single channel broad band $(8 - 12\,\mu m)$ TASCO THI-500L radiometer units operated in tandem, one set to view the sea surface and a second to view the sky in the source region of directly reflected radiation at the sea surface. The TASCO instruments have been calibrated using CASOTS blackbody cavities to better than $0.2\,^{\circ}K$. In order to minimize contamination by the sea or rain, the TASCO instruments were housed in a large box which had a small aperture cut for the radiometers to view the sea and the sky. A fan unit was used to force air out of the aperture in an effort to prevent contamination of the lenses. The sea surface roughness was determined from radar backscatter measurements made at $10.525\,GHz$ (X band) using a CW Doppler radar system attached to a standard gain horn antenna (Scientific Atlanta model 12-8.2. This experimental system was also developed by Dr. David Lyzenga from University of Michigan. The radar was attached to the upper rail of the dock at a height of $16.5\,m$ above the surface, with the antenna oriented to receive horizontally and vertically polarized radiation at an incidence angle of $45\,^{\circ}$.

Existing data sets, previously analyzed by different investigators have been made available to us for comparison purposes and use in testing of new skin layer parameterizations. All data sets include the skin and the bulk temperatures, and the heat flux components. These are:

1. R/V *John V. Vickers* (TOGA COARE): Data from two successive cruises of the R/V *John V. Vickers* during 1993 were provided for this study. The first data set was collected by the University of Hamburg as part of the TOGA-COARE experiment in February of 1993 while the ship was drifting on station in the wester Pacific warm pool about $2^{\circ}S$ and $156^{\circ}15'E$. The data set included skin and bulk temperature, downwelling solar and longwave radiation, and standard meteorological quantities. The skin temperature was measured with a Heimann $KT-19$ radiometer deployed from the port side of the ship. The bulk temperature was obtained from the ship's intake thermistor located $3\,m$ below the surface. The downwelling solar and longwave radiation measurements were taken with an Eppley pyrgeometer and a Kipp & Zonen CM 11 pyranometer respectively. The radiation measurements were processed following [21] to an accuracy of about $10\,W/m^2$. All measurements were provided in 15-minute averages.

2. R/V *John V. Vickers* (CEPEX): The second data set taken aboard the R/V *John V. Vickers* was collected by Dr. Gary A. Wick of the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado during the Central Equatorial Pacific Experiment (CEPEX) in March, 1993. The cruise took place from the Solomon Islands to Los Angeles, passing by the Christmas Islands. The T_{skin} was determined using the Multi-band Infrared Sea-Truth Radiometric Calibrator-MISTRC (Ophir Corporation, Littleton, CO) to an absolute accuracy of $\sim\ 0.1^{\circ}K$. Skin temperature measurements from the $4.025\,\mu m$ polarized channel and remaining quantities were provided in 20-minute averages. Bulk temperatures were taken continuously at a depth of $\sim\,3\,m$ with the ship's intake thermistor. Details of the calculation of the net heat flux are described by [25].

3. F/S *Meteor*: This data set was collected by the University of Hamburg aboard the German F/S Meteor during October and November of 1984. The measurements were taken in the northeast Atlantic Ocean between 21 ° and $50^{\circ}N$ and between 0° and $28^{\circ}W$. The cruise originated in Portugal, then headed for the Canary Islands, and ended in the United Kingdom. Provided measurements included skin temperature, bulk temperature at a depth of $2\,m$, downwelling solar and longwave radiation, and standard meteorological quantities such as air-temperature, wind speed and direction, and wet bulb temperature, all averaged to a 30-minute temporal resolution. Details of the measurements, accuracies and data analysis were presented by [21].

4. R/P *Flip*: Two data sets taken aboard the R/P *Flip* were collected by Dr. Andrew Jessup of the Applied Physics Laboratory (APL) at the University of Washington in January, 1992 and during the Coastal Ocean Probing Experiment (COPE) in September, 1995. These data sets were collected off the coast of Southern California and off the coast of Oregon, respectively. In both experiments, the T_{skin} was measured to an absolute accuracy of $\sim\ 0.1^{\circ}K$ with a Heimann model $KT-19$ infrared radiometer operating at wavelengths of $8 - 14\,\mu m$. The

radiometer was deployed from the port boom $10\,m$ above the sea surface with a FOV of $\sim 2^\circ$ (15° incidence angle). A wave following thermistor chain of five Sea-Bird model $SBE-3$ oceanographic thermometers provided a vertical temperature profile in the top $5\,m$. The T_{bulk} was taken as the temperature at a depth of $0.1\,m$. Details of the net heat flux computation are given by [29] and follow the standard bulk formulae. All measurements were provided in 1-minute averages.

5. R/V *Roger Revelle:* A data set provided by Dr. Peter Minnett from the Rosenstiel School of Marine and Atmospheric Science, University of Miami, was taken aboard the R/V *Roger Revelle* while on passage from Hawaii to Christchurch, New Zealand, between September 29th and October 12th of 1997. During this experiment, the skin sea surface temperature was radiometrically determined using the Marine Atmosphere Emitted Radiance Interferometer - MAERI [18]. The MAERI is an infrared radiometric interferometer with continuous on board calibration that can provide T_{skin} to an absolute accuracy of $0.05\,^\circ K$. The interferometer was deployed from the starboard O2 deck, $8\,m$ above the surface, at a 55° incidence angle. The bulk temperature was estimated using the ship's thermosalinigraph measurements from about $5-m$ depth. Provided measurements also included downwelling solar and longwave radiation, and standard meteorological quantities from the Wpak. These quantities were facilitated in 10-minute averages.

6. NOAAS *Ronald H. Brown:* The data set taken aboard the NOAAS *Ronald H. Brown* was collected by Dr. Andrew Jessup in collaboration with Dr. Gary A. Wick during the GAS EXchange Experiment (GASEX) between May and June of 1998. The primary portion of the experiment was conducted in the North Atlantic. Data are also available during transit legs between Miami, Lisbon, and the Azores. Instrumentation from both the University of Washington and the University of Colorado were on board the NOAA ship during GASEX. The University of Washington operated the same Heimann $KT-19$ radiometer (A. Jessup, APL) used during COPE but at a 30° incidence angle. All quantities were provided in 10-minute averages. The University of Colorado operated the Ship of Opportunity Sea Surface Temperature Radiometer - SOSSTR (C. Donlon and W. Emery, CCAR). See the ROSSA-1998 experiment for a detailed explanation of the SOSSTR radiometer.

7. R/V *Franklin:* This data set was collected aboard the R/V *Franklin* by Dr. Ian J. Barton of the CSIRO Marine Research Laboratory of Australia, between March 12th and April 8th, 1999. The experiment took place between Brisbane, Australia and New Caledonia. Two radiometers were on board, the DAR011 (radiometer developed by Dr. Barton at CSIRO) and a TASCO radiometer, both mounted at 45° incidence angle. Even though only the DAR011 measurements were included on the final analysis, the Tasco sky measurements were useful in providing an estimate of the net longwave radiation in the absence of Eppley pyranometer data. The bulk temperature was estimated using the ship's thermosalinigraph measurements from about $3-m$ depth. All the necessary quantities were averaged to a 10-minute temporal resolution.

A map of the cruise tracks from all the experiments just described is shown in Fig. 3. A summary of the bulk temperature depths and temporal resolutions of the previous data sets is also presented in Table 1.

NEW IDEOLOGY

The physical processes that govern the magnitude of ΔT can vary with environmental conditions. Three different possible mechanisms are shown schematically in Fig. 4. These mechanisms include *free convection, forced convection driven by wind shear stress*, and *forced convection driven by microscale wave breaking.*

During *free convection* the turbulent transport of heat is buoyancy-driven. Since the cool skin is denser than the underlying water it will become gravitationally unstable and tend to sink. Evaporation generates a salinity gradient which also contributes to the gravitational instability. During free convection, mean flow and wind shear stress are absent (non-existent or very low winds). As a result, ΔT is controlled primarily by the net heat flux.

Forced convection is when the micro-scale turbulence is sustained by mechanical forces. The two forcing mechanisms under consideration arise from either shear flow instabilities generated by the surface wind stress, or from the turbulence produced by small-amplitude surface wave effects, mainly, breaking of waves without air entrainment. During forced convection driven by wind shear stress, ΔT is regulated both by the net heat flux and the wind shear stress. During microscale breaking (capillary waves and capillary rollers or short gravity waves [16]), the skin layer is temporarily absent and no significant temperature gradients exist at the air-sea interface. Once this layer is disrupted by microscale breaking, the time it takes for the molecular layer to recover (skin layer recovery time) depends on the

Table 1: Depth of the Intake Temperature and Temporal Average

Cruise	Depth T_{bulk}	Temporal avg
Cepex 1993	3.0 m	20 min
Coare 1993	3.0 m	15 min
Cope 1995	0.1 m	10 min
Flip 1992	1.0 m	20 min
Franklin 1999	3.0 m	10 min
Gasex/Brown 1998	0.5 m	10 min
Meteor 1984	2.0 m	30 min
Revelle 1997	5.0 m	10 min
Rossa a & b 1996	6.0 m	5 min 25 min
Rossa 1998	6.0 m	10 min

heat flux. The time between renewal events (surface renewal time scale), on the other hand, is dictated by the periodicity of the breaking events and therefore independent of both, heat flux and wind speed. Under these circumstances, the disruption of the skin layer by microscale breaking can be significant even under intermediate winds [28]. If the breaking frequency is high enough so that the recovery of the molecular layer is interrupted by successive breaking events, then ΔT will appear to be independent of both the heat flux and the wind stress, and will be dictated solely by the turbulent structure of the mixed layer defined by the eddy diffusivity.

In general these processes coexist in the form of a hybrid turbulent regime known as *mixed convection*. It is important to emphasize that these processes are not mutually exclusive and can work simultaneously to regulate ΔT. In radiometric observations and numerical models, ΔT is a local variable, commonly averaged over some suitable interval of time of the order of minutes. The important implications of temporal averaging are beneficial for the improvement of experimental heat flux results. However, the differences in the physics must be understood and the variability of the dominant mechanisms that can coexist must be accounted for.

The presence of free convection serves to amplify the forced convective eddies generated by vertical wind shear or wave effects and vertical transfer processes are substantially enhanced as a result. This aspect is supported by recent data where the renewal time associated with free convection, $t_{r,conv}$, is plotted against the time computed from observations, $t_{r,obs}$, under the hypothesis that the surface renewal theory holds. These results suggest that *the observed renewal time* is bounded above by the free convective time scale. If in fact the convective time provides an upper limit for the renewal time scale and hence for ΔT, then the cool skin effect is ultimately limited by static stability.

Based on the previous considerations, we have introduced a new parameterization for ΔT of the form:

$$\begin{aligned} \Delta T_{srm} \quad &\propto \quad W_{conv}\,\Delta t_{r,\,conv} + W_{shear}\,\Delta t_{r,\,conv}\left(\frac{t_{r,\,shear}}{t_{r,\,conv}}\right)^{\frac{1}{2}} \\ &+ \quad W_{shearsat}\,\Delta t_{r,\,conv}\left(\frac{t_{r,\,shearsat}}{t_{r,\,conv}}\right)^{\frac{1}{2}} + W_{capil}\,\Delta t_{r,\,conv}\left(\frac{t_{r,\,capil}}{t_{r,\,conv}}\right)^{\frac{1}{2}} \\ &+ \quad +W_{\mu sb}\,\Delta t_{r,\,conv}\left(\frac{t_{r,\,\mu sb}}{t_{r,\,conv}}\right)^{\frac{1}{2}} + W_{lsb}\,\Delta t_{r,\,conv}\left(\frac{t_{r,\,lsb}}{t_{r,\,conv}}\right)^{\frac{1}{2}}. \end{aligned} \tag{1}$$

where W_{conv}, W_{shear}, $W_{shearsat}$, W_{capil}, $W_{\mu sb}$, and W_{lsb} are weighting functions that determine the relative importance of free convection, forced convection driven by wind shear stress and saturated shear, and forced convection driven by capillary waves, microscale wave breaking, and capillary rollers (short-gravity waves or large-scale breaking), respectively. These weights assume discrete values depending on the number of physical processes working simultaneously to regulate ΔT, i.e, $W_i = 1, 1/2, 1/3$ if one, two, or three (no more than three mechanisms seem to coexist at any given time) of the driving mechanisms under consideration contribute to changes in ΔT, or $W_i = 0$ if a type of mechanism does not contribute at all. The number of mechanisms involved seems to be dependent on certain ranges of the space domain of the log-log relationship between the observed renewal time $t_{r,obs}$ and the renewal time associated with free convection, $t_{r,conv}$, as it can be seen from Fig. 5. The remaining terms in the above parameterization are defined as follows: the $\Delta T_{r,conv}$ is the bulk-skin temperature deviation for free convection and renewal time $t_{r,conv}$ in their conventional forms [11]; $t_{r,shear}$ is the renewal time scale for forced convection driven by wind stress as defined by [23]; $t_{r,shearsat}$, $t_{r,capil}$, $t_{r,\mu sb}$ and $t_{r,lsb}$ are new renewal times we have developed for shear saturation (at higher wind speeds, the energy transfer from the air flow to the ocean turbulence tends to saturate and most of the energy from the wind stress is consumed by wave growth), capillary waves, microscale breaking, and large-scale breaking. Evaluation of the new parameterization using the data from the different cruises is shown in Fig. 6. The inclusion of parameters representing wave processes improved the correlation considerably, from ~ 0.3 to 0.94. This result illustrates that the model produces sea surface temperature deviations that are statistically similar to the observed ΔTs. The new model also seems to be able to accurately predict ΔT under the full range of environmental conditions encountered in this study.

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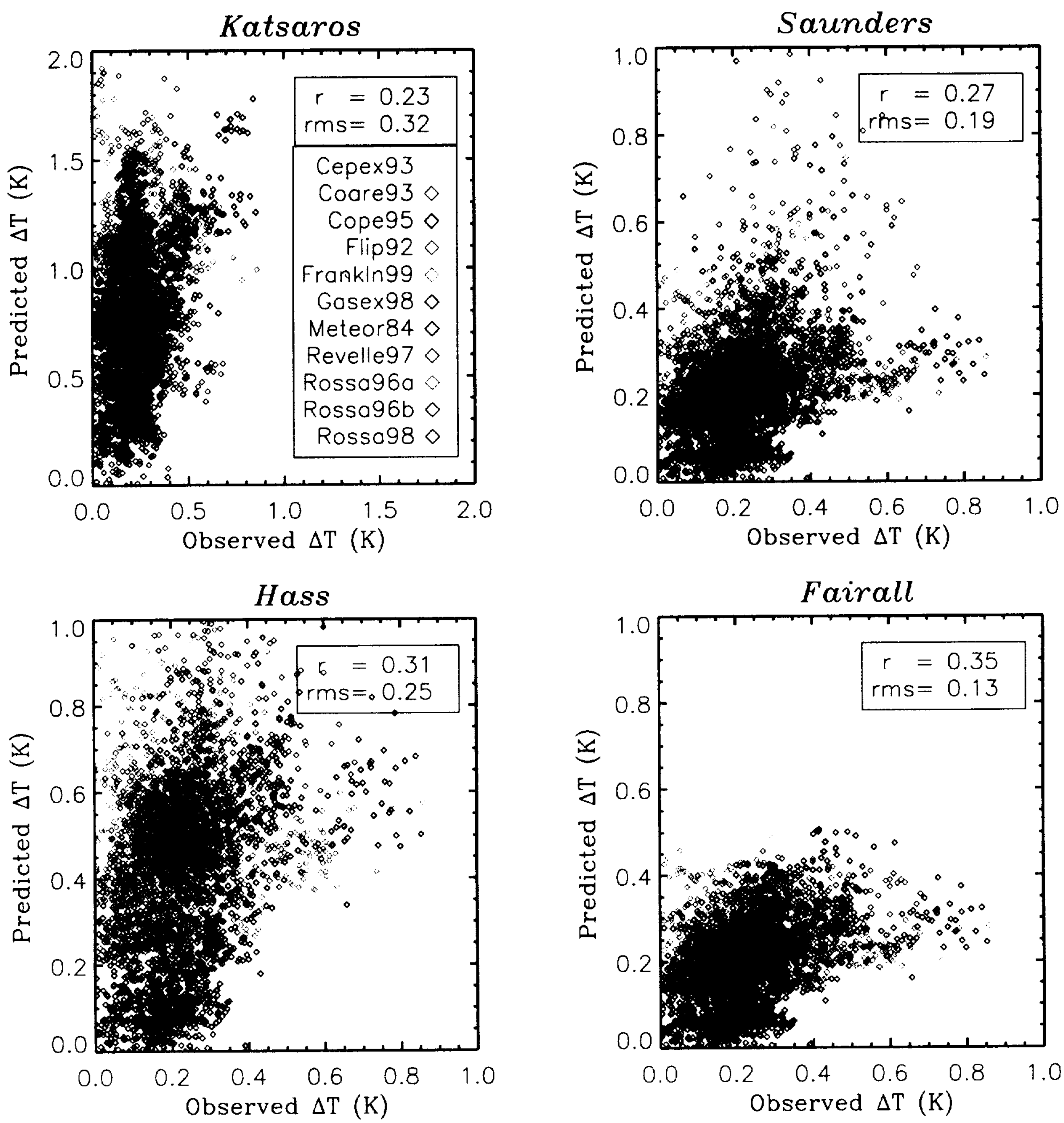


Figure 1: Observed ΔT against model predicted ΔT for 4 different parameterizations and 10 research cruises

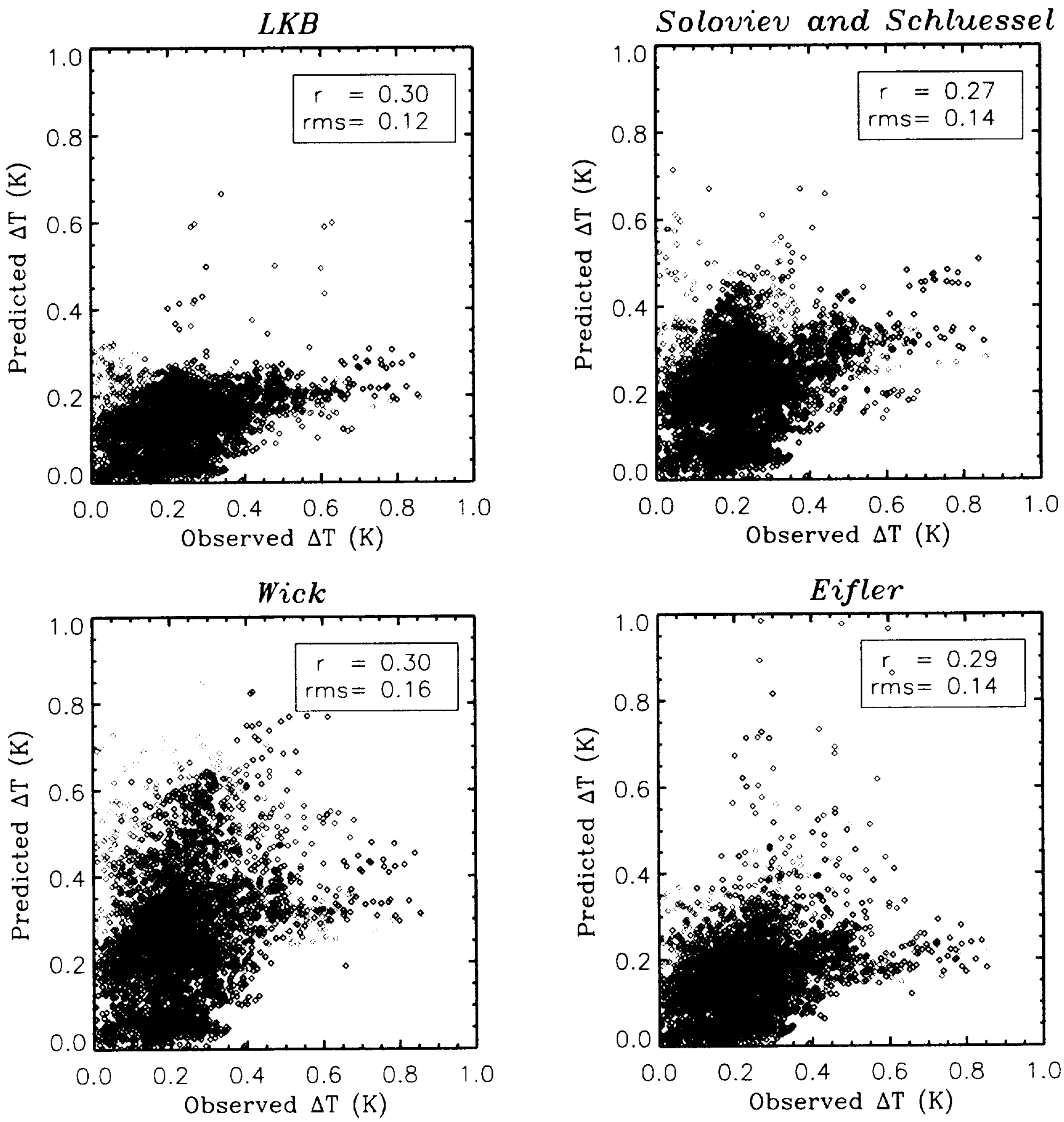
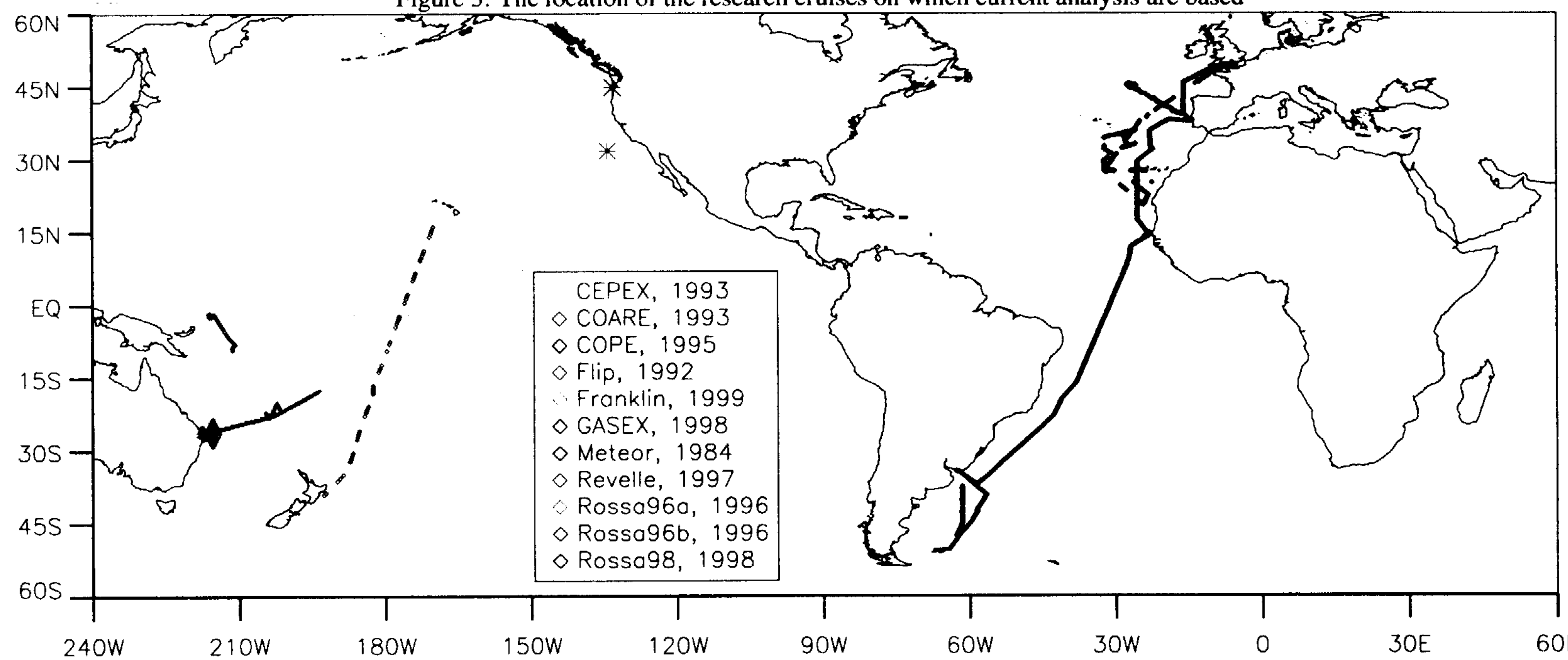


Figure 2: Observed ΔT against model predicted ΔT for 4 different parameterizations and 10 research cruises

Figure 3: The location of the research cruises on which current analysis are based



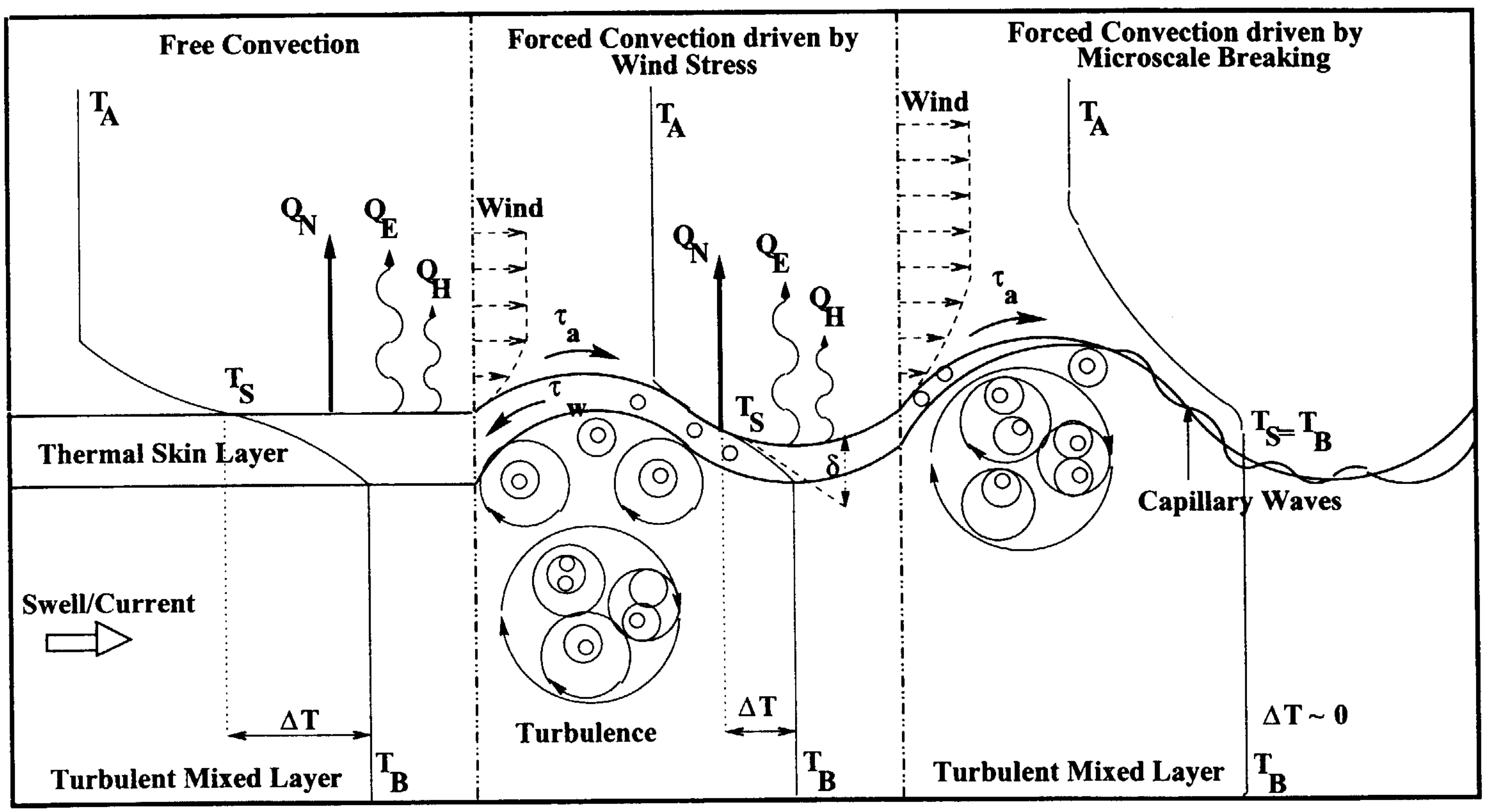


Figure 4: Physical regimes of the skin layer

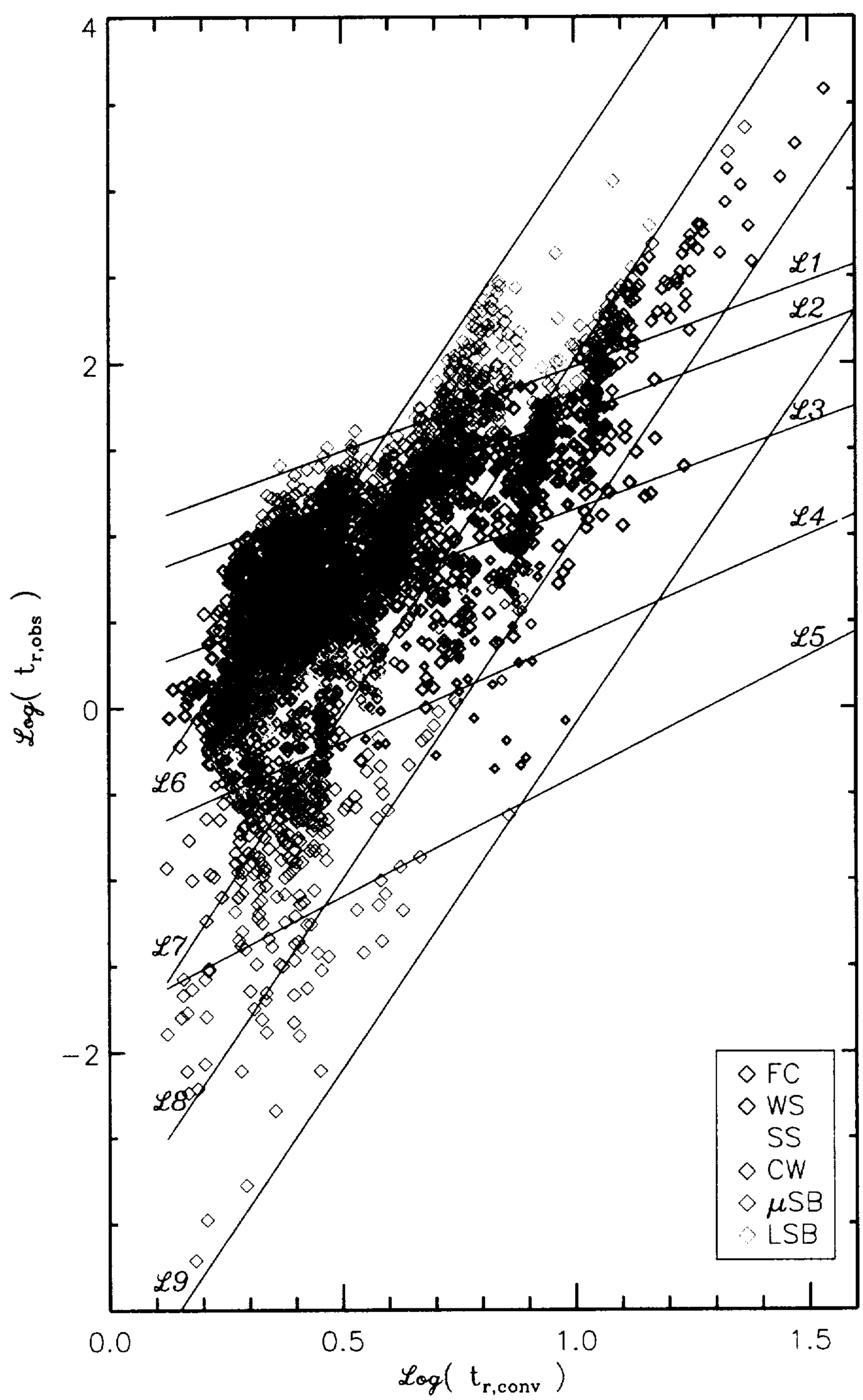


Figure 5: $\log(t_{r,obs})$ vs. $\log(t_{r,conv})$. The different colors correspond to ranges in which different combinations of driving mechanisms contribute to ΔT.

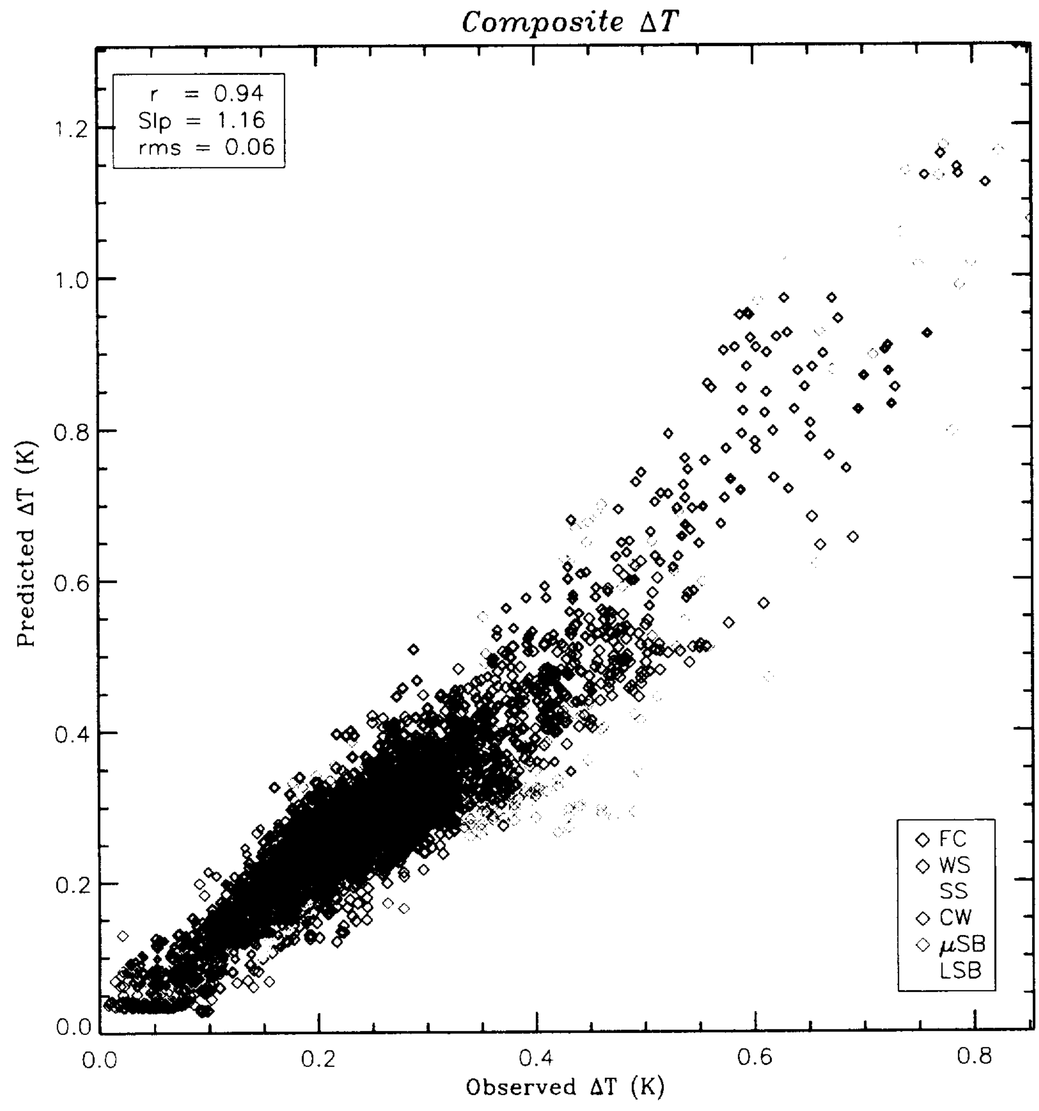


Figure 6: Observed ΔT against model predictions based on the new ΔT parameterization